F. SCAN MDCS FOR SECTION 7.3

The methodology used to determine the scan MDC is based on NUREG-1507 (NRC 1998b). An overview of the approach to determine scan MDCs follows:

- Calculate the fluence rate relative to the exposure rate (FRER) for the range of energies of interest (Section F.1),
- Calculate the probability of interaction (P) between the radiation of interest and the detector (Section F.2),
- Calculate the relative detector response (RDR) for each of the energies of interest (Section F.3),
- Determine the relationship between the detector's net count rate to net exposure rate in counts per minute per microRoentgen per hour, (cpm per μR/h, Section F.4),
- Determine the relationship between the detector response and the radionuclide concentration (Section F.5),
- Obtain the minimum detectable count rate (MDCR) for the ideal observer, for a given level of performance, by postulating detector background and a scan rate or observation interval (Section F.6), and
- Relate the MDCR for the ideal observer to a radionuclide concentration (in Bq/kg) to calculate the scan MDC (Section F.7).

F.1 Calculate the Relative Fluence Rate to Exposure Rate (FRER)

For particular gamma energies, the relationship of NaI scintillation detector count rate and exposure rate may be determined analytically (in cpm per μR/h). The approach is to determine the gamma fluence rate necessary to yield a fixed exposure rate (μR/h) as a function of gamma energy. The fluence rate, following NUREG-1507 (NRC 1998b), is directly proportional to the exposure rate and inversely proportional to the incident photon energy and mass energy absorption coefficient. That is,

$$\mathit{Fluence\ Rate}(\mathrm{FRER}) \propto \dot{X}\,\frac{1}{E_\gamma}\,\frac{1}{(\mu_{en}/\rho)_{air}} \qquad \textbf{(F-1)}$$

Where:

$\dot{X}$	= the exposure rate (set equal to 1 μR/hr for these calculations)
E_γ	= energy of the gamma photon of concern (keV)
$(\mu_{en}/\rho)_{air}$	= mass energy absorption coefficient in air at the gamma photon energy of concern (cm^2/g)

The mass energy absorption coefficients in air are presented in Table F-1 (natural uranium) and Table F-2 (natural thorium) along with the calculated fluence rates (up to a constant of proportionality, since only the ratios of these values are used in subsequent calculations). Note that while the mass energy absorption coefficients in air, $(\mu_{en}/\rho)_{air}$, are tabulated values (NIST 1996), the selected energies are determined by the calculation of the detector response based on radionuclide concentration (see Section F.5).

F.2 Calculate the Probability of Interaction

Assuming that the primary gamma interaction producing the detector response occurs through the end of the detector (i.e., through the beryllium window of the detector, as opposed to the sides), the probability of interaction (P) for a gamma may be calculated using Equation F-2:

$$\mathrm{P} = 1 - e^{-(\mu/\rho)_{\mathrm{NaI}}(x)(\rho_{\mathrm{NaI}})} = 1 - e^{-(0.117\ \mathrm{cm^2/g})(0.16\ \mathrm{cm})(3.67\ \mathrm{g/cm^3})} = 0.066 \text{ at } 400 \text{ keV} \qquad \textbf{(F-2)}$$

Where:

P	= probability of interaction (unitless)
$(\mu/\rho)_{NaI}$	= mass attenuation coefficient of FIDLER NaI crystal at the energy of interest (e.g., 0.117 cm^2/g at 400 keV)
x	= thickness of the thin edge of the FIDLER NaI crystal (0.16 cm)
ρ	= density of the NaI crystal (3.67 g/cm^3)

The mass attenuation coefficients for the NaI crystal and the calculated probabilities for each of the energies of interest are presented in Table F.1 (natural uranium) and Table F.2 (natural thorium). The mass attenuation coefficients for NaI were calculated using the XCOM program (NIST 1998).

53 **Table F.1 Calculation of Detector Response to Natural Uranium**

Energy (keV)	$(\mu_{en}/\rho)_{air}$ (cm^2/g)	FRER (Section F.1)	$(\mu/\rho)_{NaI}$ cm^2/g	P (Section F.2)	RDR (Section F.3)	cpm per μR/h (Section F.4)
15	1.334	0.04998	47.4	1.000	0.04998	28,374
20	0.5389	0.09278	21.8	1.000	0.09278	52,678
30	0.1537	0.2169	7.36	0.9867	0.2140	121,498
40	0.06833	0.3659	18.8	1.000	0.3659	207,725
50	0.04098	0.4880	10.5	0.9979	0.4870	276,511
60	0.03041	0.5481	6.45	0.9773	0.5356	304,123
80	0.02407	0.5193	3.00	0.8282	0.4301	244,204
100	0.02325	0.4301	1.67	0.6249	0.2688	152,606
150	0.02496	0.2671	0.611	0.3015	0.08052	45,717
200	0.02672	0.1871	0.328	0.1752	0.03278	18,613
300	0.02872	0.1161	0.166	0.09288	0.01078	6,120
400	0.02949	0.08477	0.117	0.06640	0.005629	3,196
500	0.02966	0.06743	0.0950	0.05426	0.003659	2,077
600	0.02953	0.05644	0.0822	0.04712	0.002660	1,510
662	0.02931	0.05154	0.0766	0.04398	0.002267	1,287
800	0.02882	0.04337	0.0675	0.03886	0.001685	957
1,000	0.02789	0.03586	0.0588	0.03394	0.001217	691
1,500	0.02547	0.02617	0.0470	0.02722	0.0007125	405
2,000	0.02345	0.02132	0.0415	0.02407	0.0005133	291

Table F.2 Calculation of Detector Response for Natural Thorium

Energy (keV)	$(\mu_{en}/\rho)_{air}$ (cm^2/g)	FRER (Section F.1)	$(\mu/\rho)_{NaI}$ cm^2/g	P (Section F.2)	RDR (Section F.3)	cpm per μR/h (Section F.4)
40	0.06833	0.3659	18.8	1.000	0.3659	207,725
60	0.03041	0.5481	6.45	0.9773	0.5356	304,123
80	0.02407	0.5193	3.00	0.8282	0.4301	244,204
100	0.02325	0.4301	1.67	0.6249	0.2688	152,606
150	0.02496	0.2671	0.611	0.3015	0.08052	45,717
200	0.02672	0.1871	0.328	0.1752	0.03278	18,613
300	0.02872	0.1161	0.166	0.09288	0.01078	6,120
400	0.02949	0.08477	0.117	0.06640	0.005629	3,196
500	0.02966	0.06743	0.0950	0.05426	0.003659	2,077
600	0.02953	0.05644	0.0822	0.04712	0.002660	1,510
662	0.02931	0.05154	0.0766	0.04398	0.002267	1,287
800	0.02882	0.04337	0.0675	0.03886	0.001685	957
1,000	0.02789	0.03586	0.0588	0.03394	0.001217	691
1,500	0.02547	0.02617	0.0470	0.02722	0.0007125	405
2,000	0.02343	0.02134	0.0415	0.02407	0.0005137	292
3,000	0.02057	0.01620	0.0368	0.02138	0.0003464	197

F.3 Calculate the Relative Detector Response

The relative detector response (RDR) for each of the energies of interest is determined by multiplying the FRER by P. The results are presented in Table F.1 (natural uranium) and Table F.2 (natural thorium).

F.4 Relationship Between Detector Response and Exposure Rate

Using the same methodology described in Sections F.1 through F.3, FRER, P, and RDR are calculated at the cesium-137 (^{137}Cs) energy of 662 keV and are presented in Table F.1 and Table F.2. The manufacturer of the FIDLER NaI detector provides an estimated response of the crystal in a known radiation field, which is 1,287 cpm per μR/h at the ^{137}Cs energy of 662 keV. The response at 662 keV can be used to determine the response at all other energies of interest using Equation F-3:

$$\frac{\text{cpm}}{\mu\text{R/h}}_{E_i} = \left(\frac{1{,}287\ \text{cpm}}{\mu\text{R/h}}\right) \times \frac{\text{RDR}_{E_i}}{\text{RDR}_{^{137}\text{Cs}}} \qquad \textbf{(F-3)}$$

Where:

E_i	= energy of the photon of interest (keV),
$\frac{\text{cpm}}{\mu\text{R/h}}_{E_i}$	= response of the detector for energies of interest, Table F.1 and Table F.2,
RDR_{E_i}	= RDR at the energy of interest, Table F.1 and Table F.2, and
$\text{RDR}_{^{137}\text{Cs}}$	= RDR for ^{137}Cs, Table F.1 and Table F.2.

The responses in cpm per μR/h for each of the decay energies of interest are presented in Table F.1 and Table F.2.

F.5 Relationship Between Detector Response and Radionuclide Concentration

The minimum detectable exposure rate is used to determine the MDC by modeling a specific impacted area. The relationship between the detector response (in cpm) and the radionuclide concentration (in Bq/kg) uses a computer gamma dose modeling code to model the presence of a normalized 1 Bq/kg total activity source term for natural uranium and natural thorium. The following assumptions from NUREG-1507 (NRC 1998b) were used to generate the computer gamma dose modeling runs:

- Impacted media is concrete,
- Density of concrete is 2.3 g/cm^3,

- Activity is uniformly distributed into a layer of crushed concrete 15 cm thick,
- Measurement points are 10 cm above the concrete surface,
- Areas of elevated activity are circular with an area of 0.25 m^2 and a radius of 28 cm,
- 0.051 cm beryllium shield simulates the window of the FIDLER detector, and
- Normalized 1 Bq/kg source term decayed for 50 years to allow ingrowth of decay progeny.

The weighted cpm per μR/h response (weighted instrument sensitivity [WS_i]) for each decay energy is calculated by multiplying the μR/h at 1 Bq/kg (exposure rate with buildup, R_i) by the cpm per μR/h and dividing by the total μR/h (at 1 Bq/kg) for all decay energies of interest (equation F-4):

$$WS_i = \frac{R_i \times (\text{cpm per } \mu\text{R / h})}{R_T} \tag{F-4}$$

Where:

WS_i = weighted instrument sensitivity (cpm per μR/h), and
R_i = exposure rate with buildup (μR/h)
R_T = Total exposure rate with buildup (μR/h)

Calculate the percent of FIDLER response for each of the decay energies of interest by dividing WS_i by the total weighted cpm per μR/h and multiplying by 100 percent (equation F-5):

$$\text{Percent of FIDLER response} = \frac{WS_i \times 100\%}{W_T} \tag{F-5}$$

Where:

W_T = Total WS_i weighted instrument sensitivity (cpm per μR/h).

The exposure rates for each of the decay energies of interest are presented in Table F.3 (assuming natural uranium for the source term) and Table F.4 (assuming natural thorium for the source term).

Table F.3 Detector Response to Natural Uranium

Energy keV	R_i (μR/h) (Section F.5)	cpm per μR/h (Section F.4)	WS_i (cpm per μR/h) (Section F.5)	Percent of FIDLER Response (Section F.5)
15	4.473×10^{-10}	28,374	0	0.00%
20	3.597×10^{-12}	52,678	0	0.00%
30	2.623×10^{-07}	121,498	226	0.504%
40	1.299×10^{-10}	207,725	0	0.00%
50	1.052×10^{-07}	276,511	206	0.460%
60	5.065×10^{-06}	304,123	10903	24.3%
80	1.518×10^{-06}	244,204	2625	5.86%
100	2.309×10^{-05}	152,606	24938	55.7%
150	5.138×10^{-06}	45,717	1663	3.71%
200	2.881×10^{-05}	18,613	3796	8.48%
300	2.237×10^{-07}	6,120	10	0.0216%
400	2.434×10^{-07}	3,196	6	0.0123%
500	4.208×10^{-07}	2,077	6	0.0138%
600	2.048×10^{-06}	1,510	22	0.0489%
800	1.478×10^{-05}	957	100	0.224%
1,000	5.759×10^{-05}	691	282	0.629%
1,500	1.695×10^{-06}	405	5	0.0108%
2,000	2.841×10^{-07}	291	1	0.00131%
Total	1.413×10^{-04}		44,923	100%

Table F.4 Detector Response to Natural Thorium

Energy keV	R_i (μR/h) (Section F.5)	cpm per μR/h (Section F.4)	WS_i (cpm per μR/h) (Section F.5)	Percent of FIDLER Response (Section F.5)
40	1.299×10^{-06}	207,725	10	0.266%
60	1.816×10^{-06}	304,123	21	0.544%
80	1.989×10^{-04}	244,204	1855	47.8%
100	5.027×10^{-05}	152,606	293	7.55%
150	5.862×10^{-05}	45,717	102	2.64%
200	1.135×10^{-03}	18,613	807	20.8%
300	8.922×10^{-04}	6,120	209	5.37%
400	1.105×10^{-04}	3,196	13	0.348%
500	8.146×10^{-04}	2,077	65	1.67%
600	2.218×10^{-03}	1,510	128	3.30%
800	2.892×10^{-03}	957	106	2.72%
1,000	6.443×10^{-03}	691	170	4.38%
1,500	2.062×10^{-03}	405	32	0.821%
2,000	5.822×10^{-05}	292	1	0.0167%
3,000	9.249×10^{-03}	197	69	1.79%
Total	2.619×10^{-02}		3881	100%

F.6 Calculation of Scan Minimum Detectable Count Rates

In the computer gamma dose modeling, an impacted area with a radius of 28 cm or approximately 0.25 m was assumed. Using a scan speed of 0.25 meters per second (m/s) provides an observation interval of one second.

A typical background exposure rate is 10 μR/h. Using a conversion factor based upon field measurements of 1,287 cpm per μR/h for ^{137}Cs (see Section F.4) results in an estimated background count rate of 12,870 cpm. Converting this value from cpm to counts per second (cps) using Equation F-6 results in a background of 214.5 cps.

$$b(\text{cpm}) \times \frac{1\text{ min}}{60\text{ sec}} \times i(\text{sec}) = \frac{1{,}287\text{ cpm}}{1\ \mu\text{R/h}} \times 10\ \mu\text{R/h} \times \frac{1\text{ min}}{60\text{ sec}} \times 1\text{ sec} = 214.5\text{ cps} \qquad \textbf{(F-6)}$$

Where:

b	= background count rate (12,870 cpm)
i	= the observation interval length (one second)

The MDCR is calculated using the methodology in NUREG-1507 (NRC 1998b) shown in Equations F-7 and F-8:

$$s_i = d'\sqrt{b_i} = 1.38 \times \sqrt{214.5} = 20.21\text{ counts} \qquad \textbf{(F-7)}$$

$$s_{i,\ surveyor} = \frac{d'\sqrt{b_i}}{\sqrt{p}} = \frac{1.38 \times \sqrt{214.5}}{\sqrt{0.5}} = 28.58\text{ counts}$$

$$\text{MDCR} = s_i \times (60/i) = 20.21 \times (60/1) = 1{,}212\text{ cpm} \qquad \textbf{(F-8)}$$

$$\text{MDCR}_{surveyor} = s_{i,\ surveyor} \times (60/i) = 28.58 \times (60/1) = 1{,}715\text{ cpm}$$

Where:

b_i	= the average number of counts in the background interval (214.5 counts)
i	= the observation interval length (one second)
p	= efficiency of a less than ideal surveyor, range of 0.5 to 0.75 from NUREG-1507 (NRC 1998b); a value 0.5 was chosen as a conservative value

d' = detectability index from Table 6.1 of NUREG-1507 (NRC 1998b); a value of 1.38 was selected, which represents a true positive detection rate of 95% and a false positive detection rate of 60%

s_i = minimum detectable number of net source counts in the observation interval (counts)

$s_{i,surveyor}$ = minimum detectable number of net source counts in the observation interval by a less than ideal surveyor

MDCR = minimum detectable count rate (cpm)

$\mathrm{MDCR}_{surveyor}$ = MDCR by a less than ideal surveyor (cpm)

F.7 Calculate the Scan Minimum Detectable Concentration

The scan minimum detectable concentration (MDC) can be calculated from the minimum detectable exposure rate (MDER). The MDER can be calculated using the previously calculated total weighted instrument sensitivities (WS_i), in cpm per μR/h, for natural uranium and natural thorium as shown in equations F-9 and F-10:

$$\mathrm{MDER} = \frac{\mathrm{MDCR}_{surveyor}}{W_T} \tag{F-9}$$

$$\text{Scan MDC} = C \times \frac{\mathrm{MDER}}{R_T} \tag{F-10}$$

Where:

MDER = MDER for the "ith" source term, by a less than ideal surveyor, (μR/h)

$\mathrm{MDCR}_{surveyor}$ = MDCR rate by a less than ideal surveyor (cpm), from Section F.5

W_T = Total weighted instrument sensitivity (cpm per μR/h, Table F.3 and Table F.4)

R_T = Total exposure rate with buildup (μR/h, Table F.3 and Table F.4)

C = concentration of source term (set at 1 Bq/kg in Section F.5)

Scan MDC = minimum detectable concentration (Bq/kg)

The Scan MDCs for the FIDLER were calculated using Equations F-9 and F-10, and the instrument response information from Table F.3 (assuming natural uranium as the source term) and Table F.4 (assuming natural thorium as the source term). The scan MDCs for natural uranium and natural thorium using a FIDLER are listed in Table F.5.

Table F.5 Scan MDCs for FIDLER

Source Term	$MDCR_{surveyor}$ (cpm) Section F.6	W_T (cpm per μR/h) Section F.5	MDER (μR/h) Section F.7	R_T (μR/h) Section F.5	C (Bq/kg) Section F.5	Scan MDC (Bq/kg) Section F.7
Natural Uranium	1,715	44,786	0.03829	1.413×10^{-04}	1	**271 ≈ 300**
Natural Thorium	1,715	3,881	0.4419	2.619×10^{-02}	1	**16.9 ≈ 20**

The scan MDCs of approximately 300 Bq/kg for uranium and 20 Bq/kg for thorium are both less than their respective NUREG-1640-based activity action levels of 38,000 and 330 Bq/kg, respectively.